Eternal annihilations of light photinos

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In a class of low-energy supersymmetry models the photino is a natural dark matter candidate. We investigate the effects of post-freeze-out photino annihilations which can generate electromognetic cascades and lead to photo-destruction of ^{4}He and subsequent overproduction of D and ^{3}He. We also generalize our analysis to a generic dark matter component whose relic abundance is *not* determined by the cross section of the self-annihilations giving rise to electromagnetic showers.

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I. INTRODUCTION

There are good reasons to consider models of low energy supersymmetry [1] in which dimension-3 supersymmetric breaking operators are highly suppressed. The low-energy features and possible new signatures of such attractive form of supersymmetric breaking have been extensively outlined by Farrar [2]. In most of these models photinos $\tilde{\gamma}$ and gluinos $\tilde{g}$ are very light and the lightest R-odd particle[1] may be a color-singlet state containing a gluino, the R^0, with a mass m_{R^0} in the 1 to 2 GeV range.

It has been recently pointed out by Farrar and Kolb [3] that a photino $\tilde{\gamma}$ slightly lighter than the R^0, in the mass range 100 to 1400 MeV, would survive as the relic R-odd species and might be an attractive dark-matter candidate. Indeed, they found that it is crucial to include the interactions of the photino with the R^0. The R^0 has strong interactions and thus annihilates extremely efficiently and remains in equilibrium to temperatures much lower than its mass. In these circumstances, photino freeze-out is *no longer* determined by self-annihilations into fermions pairs $\tilde{\gamma}\tilde{\gamma} \longleftrightarrow f\bar{f}$ (which would result in an unacceptable photino relic abundance for such low mass range), but occurs when the rate of reactions converting photinos to R^0's falls below the expansion rate of the Universe. The rate of the $\tilde{\gamma} - R^0$ interconversion interactions which keep photinos into equilibrium ($\tilde{\gamma}\pi \longleftrightarrow R^0\pi$) or R^0 decay/inverse decay ($\tilde{\gamma}\pi \longleftrightarrow R^0$), depends upon the densities of photinos and pions, rather then on the square of the photino density, as in the case for the self-annihilation processes. For photinos in the relevant mass range ($m_{\tilde{\gamma}} \sim 800$ MeV), the pion abundance is enormous compared to the photino abundance. Therefore the photinos stay in equilibrium to much higher values of $x \equiv m_{\tilde{\gamma}}/T$ than they would if self-annihilation were the only operative process, resulting in a smaller

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[1]R-parity is a multiplicative quantum number, exactly conserved in most of supersymmetric models, under which ordinary particles have $R = 1$ while their superpartners have $R = -1$.

relic density for a given photino mass and cross section. Light photinos with a mass in the range $1.2 \lesssim r \equiv m_{R^0}/m_{\tilde{\gamma}} \lesssim 2.2$ are cosmologically acceptable and in the range $1.6 \lesssim r \lesssim 2$ are excellent dark matter candidate.

The aim of the present paper is to investigate whether in the scenario outlined in [3], light photino self-annihilations into fermions pairs may have an impact on the successful predictions of the standard big-bang nucleosynthesis even though self-annihilations are not relevant in determining the relic photino abundance. The destructive high-energy photons coming from the self-annihilation products of primordial photinos, including $e^{\pm}$, $\mu^{\pm}$ and γ's, may indeed cause photofission of the primordially produced light nuclei [4] upsetting the agreement between big-bang nucleosynthesis and the observed element abundances.

According to the standard lore, the source of destructive high-energy photons may be neglected because self-annihilations (SA) typically freeze out at a temperature $T_{\mathrm{SA}} \sim m_{\tilde{\gamma}}/15$ (not to be confused with the freeze out temperature of the photino relic abundance $T_* \sim m_{\tilde{\gamma}}/(20-25)$ determined by $\tilde{\gamma}-R^0$ conversion). For photino masses in the dangerous range, $m_{\tilde{\gamma}}$ greater than a few MeV, this freeze-out occurs well before the light elements first become vulnerable to photodissociation at temperatures of about a few keV. By this late epoch, any photons and electrons generated before freeze-out have harmlessly thermalized. However, after freeze-out, occasional self-annihilations still may take place. Although rare on the expansion time scale, residual annihilations continue to produce high-energy photons well after nucleosynthesis ends, thereby placing the survival of the light nuclei in jeopardy [5].

We explore below the consequences of these eternal light photino self-annihilations by computing the residual annihilation rate and the corresponding photofission yields. The typical feature of the model at hand is that the production rate of dangerous high-energy photons and the relic abundance of light photinos are *not* determined by the

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same cross section, the former being dependent on the light photino thermally averaged self-annihilation cross section $\langle \sigma_{\mathrm{SA}} |v| \rangle$ and the latter by the $\tilde{\gamma} - R^0$ conversion rate. We then generalize our analysis to any case in which the relic abundance of a generic dark matter candidate X is not determined by its self-annihilation cross section, as assumed in [5], but rather by some other generic processes, a typical case being the presence of a slightly heavier particle X' (e.g., the R^0 in [3]) with relative interconversion processes $X \longleftrightarrow X'$, usually called co-annihilation [6].

II. ETERNAL ANNIHILATIONS

In the Boltzmann equation [7] for the evolution of the $\tilde{\gamma}$-number density there are several terms, including photino self-annihilation ($\tilde{\gamma}\tilde{\gamma} \to X$), co-annihilation ($\tilde{\gamma}R^0 \to X$), inverse decay ($\tilde{\gamma}\pi \to R^0$) and photino-$R^0$ conversion ($\tilde{\gamma}\pi \to R^0\pi$) (see Refs. [3,8] for a detailed analysis).

In this Section we are only interested in the terms of the Boltzmann equation which may provide a source for destructive electromagnetic cascades at low temperatures, i.e., in the terms accounting for photino self-annihilation into fermion pairs and photino pair production from light particles in the plasma.

Assuming the light annihilation products are in thermal equilibrium, these terms are of the form

$$\dot{n}_{\tilde{\gamma}} + 3H n_{\tilde{\gamma}} = -\langle \sigma_{\mathrm{SA}} |v| \rangle \left[(n_{\tilde{\gamma}})^2 - \left(n_{\tilde{\gamma}}^{\mathrm{EQ}} \right)^2 \right], \tag{1}$$

where H is the expansion-rate of the Universe

$$H = 1.66\, g_*^{1/2} \frac{T^2}{M_{\mathrm{Pl}}} = 4.4 \times 10^{-19}\, x^{-2} \left(\frac{m_{\tilde{\gamma}}}{\mathrm{GeV}} \right)\ \mathrm{GeV}, \tag{2}$$

g_* being the relativistic degrees of freedom at the temperature T, $n_{\tilde{\gamma}}^{\mathrm{EQ}}$ is the photino equilibrium number density at temperature T

$$n_{\tilde{\gamma}}^{\mathrm{EQ}}(T) = \frac{2}{(2\pi)^{3/2}} \, x^{-3/2} \, m_{\tilde{\gamma}}^3 \exp(-x), \tag{3}$$

and, finally, an overdot denotes a time derivative.

Well before photinos freeze-out, at times $t \ll t_{\mathrm{SA}}, t_*$ (dictated respectively by self-annihilation processes and $\tilde{\gamma} - R^0$ conversion), the self-annihilation rate $\Gamma_{\mathrm{SA}} = n_{\tilde{\gamma}}\langle \sigma_{\mathrm{SA}}|v|\rangle$ is faster than the expansion rate, $\Gamma_{\mathrm{SA}} \gg H$, and the photino abundance is kept at its equilibrium value, $n_{\tilde{\gamma}} = n_{\tilde{\gamma}}^{\mathrm{EQ}}$. We are interested in the epoch long after freeze-out, $t \gg t_*$, when $n_{\tilde{\gamma}} \gg n_{\tilde{\gamma}}^{\mathrm{EQ}}$ and the number density to the entropy density $Y_{\tilde{\gamma}} = n_{\tilde{\gamma}}/s$, $s = (2\pi^2/45)g_{*S}T^3$ being the entropy density at the temperature T, has ceased to decrease significantly, i.e., $Y_{\tilde{\gamma}} \simeq Y_\infty$ for $t \gg t_*$. The asymptotic value Y_∞, which is determined by the photino interactions with R^0 and does not depend on the details of $\langle \sigma_{\mathrm{SA}}|v|\rangle$ [3], may be expressed in terms of the fraction of the critical density contributed by the photino at the present epoch

$$\Omega_{\tilde{\gamma}}h^2 = \frac{\rho_{\tilde{\gamma}}}{\rho_C} = 2.8 \times 10^8 \left(\frac{m_{\tilde{\gamma}}}{\mathrm{GeV}}\right) Y_\infty, \tag{4}$$

where $\rho_C = 1.05 \times 10^{-5} \, h^2 \, \mathrm{GeV} \, \mathrm{cm}^{-3}$ is the present critical density.

Well after the freeze-out of the photino abundance, the change in time of the fraction of photino number density contributing to fermion pair production is then given by[2]

$$\dot{n}_{\tilde{\gamma}} + 3Hn_{\tilde{\gamma}} = -\langle \sigma_{\mathrm{SA}}|v|\rangle Y_\infty^2 \, s^2. \tag{5}$$

This last Equation will be our starting point in the next Sections to analyze the influence of eternal self-annihilations on primordial nucleosynthesis.

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[2] It is easy to check that for the temperature of interest here, $T \ll T_*$, self-annihilations into fermion pairs is the dominant source for photino number density depletion so that Eq. (5) actually describes the change in time of the whole photino number density.

III. ELECTROMAGNETIC CASCADES

Let us begin by examining the manner in which annihilations of light photinos into light leptons (electrons or muons) generate electromagnetic cascades in the radiation-dominated thermal plasma of the early Universe [9].

The epoch of interest for cascade nucleosynthesis has temperatures smaller than a few keV, by which time production of the light elements D, He, and Li by big-bang nucleosynthesis has completed. At this epoch, electron-positron pairs are no longer in equilibrium and blackbody photons, γ_{bb}, constitute the densest target for electromagnetic cascade development.

A cascade is initiated by a high-energy lepton (or photon) coming from the self-annihilating photinos and develops rapidly in the radiation field mainly by photon-photon pair production and inverse Compton scattering

$$e + \gamma_{bb} \rightarrow e' + \gamma', \quad \gamma + \gamma_{bb} \rightarrow e^+ + e^-. \tag{6}$$

When cascade photons reach energies too low for pair production on the blackbody photons, the cascade development is slowed and further development occurs in the gas by ordinary pair production, but with electrons still loosing energy mainly by inverse Compton scattering in the blackbody radiation

$$\gamma + Z \rightarrow Z + e^+ + e^-, \quad e + \gamma_{bb} \rightarrow e' + \gamma'. \tag{7}$$

At high energies, the cascade develops entirely on the blackbody photons by photon-photon pair production and inverse Compton scattering. The characteristic interaction rates for these processes are much higher than the expansion rate and thus one can assume the cascade spectrum is formed instantly. This spectrum is referred to as the "zero-generation" spectrum.

Since $\gamma - \gamma$ elastic scattering is the dominant process in a radiation-dominated plasma for photons just below the pair-production threshold [10], a primary photon or lepton triggers a cascade which develops until the photon energies have fallen below the maximum energy $E_{\mathrm{max}}(T) \simeq m_{\mathrm{e}}^2/(22\,T)$ corresponding to the energy for which the mean free paths against $\gamma - \gamma$ scattering and $\gamma - \gamma$ pair production are equal [11].

When E_{max} is less than the threshold for photodisintegration of ^{4}He nuclei (approximately 20 MeV), cascade nucleosynthesis is inefficient. This condition restricts the epoch of cascade nucleosynthesis to $T \lesssim 0.5$ keV. At temperatures between about 10^{-4} and 0.5 keV, where the subsequent cascade development is via ordinary pair production and inverse Compton scattering, the photons survive for a time determined by either the energy loss rate for compton scattering or the interaction rate for ordinary pair production in the gas. During this time they can produce light nuclei by photodisintegration. The electrons and positrons give rise to first generation photons as a result of inverse Compton scattering. These first generation photons then produce the second generation photons and so on. Each generation of photons is shifted to low energies because the inverse Compton scattering is in the Thompson regime and only one to two generations of photons are sufficiently energetic to induce cascade nucleosynthesis.

At $T \lesssim 10^{-4}$ keV, when interaction times become larger than the Hubble time, only the zero-generation photons are produced and the effectiveness of the cascade nucleosynthesis diminishes as T drops.

A detailed numerical cascade calculation including all the effects has been recently performed by Protheroe $et\ al.$, [12] to find the number of deuterium and ^{3}He nuclei produced by the cascade initiated at a redshift z. It was shown that because of the almost instant formation of the zero-generation spectrum, the exact shape of the γ-ray or electron injection spectrum is of no consequence for further cascade development, and only the total amount of injected energy is relevant. The epoch of cascade nucleosynthesis

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is limited by $T_{\max}$ and $T_{\min}$. The maximum temperature is determined by the condition that the maximum energy of photons in the cascade spectrum, $E_{\max}$, must be larger than the threshold for D or ^{3}He production on ^{4}He, $E_{\max} \simeq 20$ MeV. This condition result in $T_{\max} \simeq 0.57$ keV. The effectiveness of D and ^{3}He production decreases as T decreases. The reason for that is not the decrease of the density of ^{4}He, but rather the decrease in number of low-energy photons in the cascade. In fact, the lower the temperature, the higher the photon energies in the cascade and therefore a smaller fraction of the photons in cascade nucleosynthesis [12].

At $T \lesssim T_{\min} \simeq 2.4 \times 10^{-4}$ keV the cascade photons can be directly observed and the upper limit for the isotropic γ-ray flux at $10 - 200$ MeV is more restrictive for the cascade production than nucleosynthesis. Therefore the most effective epoch for cascade nucleosynthesis corresponds to temperatures in the range $10^{-4} - 0.5$ keV [12].

It was also shown that the role of $\gamma\gamma \to \gamma\gamma$ scattering is important for epochs with temperatures $T \gtrsim 1.2 \times 10^{-2}$ keV when the scattered photons do not interact again with the target photons, but are just redistributed over the spectrum producing a small bump before the cut-off energy $E_{\max}$.

IV. APPLICATION AND DISCUSSION

From the detailed analysis performed in [12], the number of ^{3}He and D nuclei produced by a single cascade of total energy E_0 is $\mathcal{N}(^3\mathrm{He}) \sim (0.1 - 1)\, E_0\ \mathrm{GeV}^{-1}$ and $\mathcal{N}(\mathrm{D}) \sim (1 - 6) \times 10^{-3}\, E_0\ \mathrm{GeV}^{-1}$.

Let us imagine that eternal self-annihilations of light photinos into lepton pairs are the only source of energetic cascades. In such a case, the total fraction $(^3\mathrm{He}+\mathrm{D})/\mathrm{H}$ at

the present epoch reads

$$\begin{aligned}
\frac{^3\text{He} + \text{D}}{\text{H}} &= f_c \left(\frac{m_{\tilde{\gamma}}}{\text{GeV}}\right) \int dt \, \frac{\dot{n}_{\tilde{\gamma}}^c}{n_\text{H}} \left[\mathcal{N}(^3\text{He}, t) + \mathcal{N}(\text{D}, t)\right] \\
&= -f_c \left(\frac{m_{\tilde{\gamma}}}{\text{GeV}}\right) \int \frac{dt}{n_\text{H}} \left[\mathcal{N}(^3\text{He}, t) + \mathcal{N}(\text{D}, t)\right] \langle \sigma_\text{SA} |v| \rangle Y_\infty^2 \, s^2,
\end{aligned} \tag{8}$$

where f_c is the fraction of mass $m_{\tilde{\gamma}}$ transferred to cascade energy, $\mathcal{N}(^3\text{He}, t)$ and $\mathcal{N}(\text{D}, t)$ are the number of ^{3}He and D nuclei produced at the time t per GeV by the total electromagnetic cascade [12], n_H is the hydrogen number density per comoving volume and $\dot{n}_{\tilde{\gamma}}^c$ represents the time derivative of the photino number density per comoving volume.

Photino self-annihilations in which the final state is a lepton-antilepton pair involve the t-channel exchange of a virtual slepton between the photinos, producing the final fermion-antifermion pair. In the low-energy limit the mass $m_{\tilde{l}}$ of the slepton is much greater than the total energy exchanged in the process and the photino-photino-fermion-antifermion operator appears in the low-energy theory as a coefficient proportional to $e_i^2 / m_{\tilde{l}}^2$, with e_i the charge of the final-state fermion. Also, as there are two identical fermions in the initial state, the annihilation proceeds as a p-wave, which introduces a factor v^2 in the low-energy cross section [13]. The resultant low-energy photino self-annihilation cross section is [14]

$$\langle \sigma_\text{SA} |v| \rangle = 8\pi \alpha_\text{em}^2 \sum_i e_i^4 \frac{m_{\tilde{\gamma}}^2}{m_{\tilde{l}}^4} \frac{v^2}{3} \simeq 2.3 \times 10^{-11} \left(\frac{T}{m_{\tilde{\gamma}}}\right) \left(\frac{m_{\tilde{\gamma}}}{\text{GeV}}\right)^2 \left(\frac{m_{\tilde{l}}}{100 \text{ GeV}}\right)^{-4} \text{mb}, \tag{9}$$

where we have used for the relative velocity $v^2 = 6/x$ and we have summed over e and μ assuming a common slepton mass $m_{\tilde{l}}$ for selectron and smuon scalar fields.

Recalling that for a radiation-dominated Universe $t = 0.301 \, g_*^{-1/2} \left(M_\text{Pl}/T^2\right)$, assuming baryonic mass is 77% hydrogen by mass, and making use of Eq. (5), we have numerically evaluated the time-integral of the right-hand side of Eq. (8) and obtained the present total fraction (^{3}He+D)/H generated by the electromagnetic showers induced by eternal

photino self-annihilations into lepton-antilepton pairs

$$\frac{^{3}\text{He} + \text{D}}{\text{H}} \simeq 9.4 \times 10^{-12} \left(\frac{f_c}{0.77 \, \Omega_{\text{B}}}\right) (\Omega_{\tilde{\gamma}} \, h)^2 \left(\frac{m_{\tilde{l}}}{100 \ \text{GeV}}\right)^{-4}. \tag{10}$$

The upper limit inferred from measurements of ^{3}He in meteorites and the solar wind making assumptions about stellar processing and galactic chemical evolution is $(^{3}\text{He}+\text{D})/\text{H} \lesssim 1.1 \times 10^{-4}$ [15]. This bound translates from Eq. (10) into a lower limit on the slepton mass[3]

$$m_{\tilde{l}} \gtrsim 1.7 \left(\frac{f_c}{0.77 \, \Omega_{\text{B}}}\right)^{1/4} (\Omega_{\tilde{\gamma}} \, h)^{1/2} \ \text{GeV}. \tag{11}$$

We notice that this lower bound on the slepton mass is *independent* of the photino mass and thus holds for the entire range of cosmological interest of the photino mass $1.6 \lesssim r \lesssim 2$ [3]. Since the lower limit on $m_{\tilde{l}}$ given in Eq. (11) is weaker than any other present experimental lower bound on slepton masses, we may conclude that eternal self-annihilations of light photinos do not jeopardize the successful predictions of primordial nucleosynthesis.

Let us now generalize our analysis to the case in which the relic abundance of a generic light dark matter candidate X is determined by some processes other than its self-annihilation cross-section into leptons, which we parameterize as $\langle \sigma_{\text{SA}} |v| \rangle = \sigma_0 (T/m_X)^n$, where we have assumed that either s-wave ($n = 0$) or p-wave ($n = 1$) annihilations dominate[4]; it is straightforward to generalize to the case where both contribute. For instance, one can envisage the situation in which the dark matter component X is slightly degenerate with a particle X' and that interconversion processes $X \longleftrightarrow X'$ keep X in

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[3]Note, however, that very recent measurements of D/H are closer to $(2 - 5) \times 10^{-4}$ [16] and, if such higher values for $(^{3}\text{He}+\text{D})/\text{H}$ were adopted, the upper limits we derive would be correspondingly higher.

[4]This may happen, for instance, when explicit sfermion mixing [18] or CP-violating phases [19] in low-energy supersymmetric models greatly enhance the self-annihilation cross-section of the lightest supersymmetric particles into fermions removing the p-wave suppression.

equilibrium even after self-annihilations have frozen out, regardless of the strength of the interactions governing the X' abundance. This case is rather different from the one analyzed in [5] where it was assumed that the same cross section determines both the self-annihilation rate and the relic abundance of the X-particles.

By making use of Eqs. (1) and (8), we have numerically evaluated the present fraction of $(^3\mathrm{He}+\mathrm{D})/\mathrm{H}$ generated by electromagnetic cascades induced by eternal self-annihilations of X's into leptons. Adopting the upper limit $(^3\mathrm{He}+\mathrm{D})/\mathrm{H} \lesssim 1.1 \times 10^{-4}$ [15] we find

$$
\left(\frac{\sigma_0}{10^{-38}\ \mathrm{cm}^{-2}}\right) \left(\frac{m_X}{\mathrm{GeV}}\right)^{-1} \lesssim 2.7 \times 10^7 \left(\frac{f_c}{0.77\ \Omega_\mathrm{B}}\right)^{-1} (\Omega_X\, h)^{-2} \quad \text{for}\ n = 0,
$$

$$
\left(\frac{\sigma_0}{10^{-38}\ \mathrm{cm}^{-2}}\right) \left(\frac{m_X}{\mathrm{GeV}}\right)^{-2} \lesssim 6.6 \times 10^{12} \left(\frac{f_c}{0.77\ \Omega_\mathrm{B}}\right)^{-1} (\Omega_X\, h)^{-2} \quad \text{for}\ n = 1.
$$

$$(12)$$

Once the model-dependent cross section σ_0 is known, one can apply the above limits to find the appropriate bounds on the parameter space of the model.

So far we have been assuming that the generic dark matter component X eternally self-annihilates only into lepton-antilepton pairs. When hadronic channels are open, D is produced by hadronic showers and this requires reconsideration of the constraint derived above. In fact, even if light photinos self-annihilate only into lepton pairs, the resulting electromagnetic cascades will be effectively hadronic if $E_\gamma \varepsilon_\gamma \gtrsim \mathrm{GeV}^2$, where E_γ is the typical energy of a cascade photon and ε_γ is the low energy of a blackbody photon; furthermore there is always a $\sim 1\%$ probability for the virtual decay photon to convert into a quark-antiquark pair over threshold. Hence hadronic showers will be generated if $m_X \gtrsim 1$ GeV even if X-particles do not have specific self-annihilation channels into quark pairs (see Reno and Seckel [5]).

As discussed in detail by Dimopoulos *et al.* [17], the main effect of hadronic cascades is the destruction of the ambient $^4\mathrm{He}$ and the creation of D (while it is photodestroyed by

electromagnetic showers), ^{3}He, ^{6}Li, and ^{7}Li. Even though the final answer on the light element abundances may be provided only by an extensive numerical analysis involving both hadronic and electromagnetic cascades, since the constraints on the primordial abundance of ^{6}Li and ^{7}Li are so stringent [9] one might expect that energy released by self-annihilations of X-particles under the form of quark-antiquark pairs must be very small in order not to overproduce lithium. This suppression may happen either imposing that the X-particle is sufficiently light so that emission of quark pairs is phase-space suppressed or assuming that the self-annihilation cross section is enough suppressed, which may happen if the virtual particles mediating the process are very heavy.

In conclusion, we have investigated the effect on big-bang nucleosynthesis predictions of a very light photino predicted in low-energy supersymmetry models in which dimension-3 supersymmetric breaking operators are suppressed [2]. We have found that eternal photino self-annihilations into fermion pairs that take place around 10^5 to 10^6 sec after the big-bang cannot significantly alter the primordial abundances of light elements when taking into account the present experimental limits on the slepton masses.

We have also generalized our study to the case of a generic dark matter component X whose relic abundance is not determined by the self-annihilation cross section into leptons, but by some other processes, *e.g.,* co-annihilations with a slightly heavier particle X'. Limits on the self-annihilation cross section and mass of the X-particle have been given by requiring that electromagnetic cascades generated by the eternal self-annihilations of the X-particle do not jeopardize the predictions of the big-bang nucleosynthesis.

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